2016-09

Optimizing Fuel Delivery Ashore: An Analysis on Fuel Delivery from the Ship to the Shore

Graziani, Michael; Konicki, Andrew; Duchene, Eric

Monterey, California. Naval Postgraduate School

http://hdl.handle.net/10945/56321

NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

MASTERS OF SYSTEM ANALYSIS CAPSTONE PROJECT

Optimizing Fuel Delivery Ashore

An Analysis on Fuel Delivery from the Ship to the Shore

By

Lieutenant Colonel Michael Graziani, USMC; Major Andrew Konicki, USMC;
Major Eric Duchene, USMC

Advisors: Dr. Michael Atkinson, PhD; Dr. Kyle Lin, PhD
Professor: CAPT Douglas E. Otte USN (Ret.)

THIS PAGE INTENTIONALLY LEFT BLANK

Optimizing Fuel Delivery Ashore

An Analysis on Fuel Delivery from the Ship to the Shore

Team Members:

Lieutenant Colonel Michael Graziani, USMC

Major Andrew Konicki, USMC

Major Eric Duchene, USMC

Advisors:

Dr. Michael Atkinson, PhD
Naval Postgraduate School

Dr. Kyle Lyn, PhD
Naval Postgraduate School

Submitted in partial fulfillment of the
requirements for the degree of

MASTERS OF SYSTEM ANALYSIS

from the

NAVAL POSTGRADUATE SCHOOL
September 26, 2016

THIS PAGE INTENTIONALLY LEFT BLANK

Table of Contents

List of Tables

List of Figures

Appendix A

Acronyms and Abbreviations

A2AD:	Anti-Access/Area Denial
ACE:	Aviation Combat Element
ADGR:	Aviation Delivered Ground Refueling
ARG	Amphibious Ready Group
ATGM:	Anti-Tank Guided Missile
CAS:	Close Air Support
CDCM:	Coastal Defense Cruise Missiles
DCA	Deputy Commandant, Aviation
EDL:	Equipment Density List
FARP	Forward Arming and Refueling Point
Kts:	Knots
LHA/LHD:	Amphibious Assault Ship
LCAC:	Landing Craft Air Cushioned
LCU:	Landing Craft, Utility
LPD:	Amphibious Transport Dock
LSD:	Dock Landing Ship
LVSR:	Logistics Vehicle System Replacement
MAGTF:	Marine Air Ground Task Force
MATS:	Mission Auxiliary Tank System
MEU:	Marine Expeditionary Unit
MTVR:	Medium Tactical Vehicle Replacement
NAE:	Naval Aviation Enterprise
nm:	Nautical Mile
RPG:	Rocket Propelled Grenade
SAM:	Surface to Air Missile
SSC:	Ship to Shore Connector
STS:	Ship to Shore
TBFDS:	Tactical Bulk Fuel Delivery System
T/M/S:	Type/Model/Series
VMM:	Marine Medium Tiltrotor Squadron

Executive Summary

Problem Statement

- There are an increasing number of countries that are obtaining or improving their Anti-Access/Area Denial (A2AD) capabilities that threaten an Amphibious Readiness Group (ARG)/Marine Expeditionary Unit's (MEU) ability to push supplies ashore after an amphibious assault. As A2AD capability increases, so does the distance from which the ARG/MEU must operate.
- The Marine Corps relies on the supply of fuel to conduct modern warfare. An adversary's A2AD capabilities that push the ARG/MEU farther from shore, strains the logistic system's ability to deliver the right amount of fuel at the right place and time.

Overall Objective

The study objective was to determine an acceptable and robust mix of connectors to deliver fuel ashore to meet the demand of a MEU operating within an A2AD environment. The study scenarios were based against a non-descript, near-peer/regional adversary coastal country. Connector effectiveness was analyzed in various mixes which took into account:

1) Environmental conditions
2) Distance from shore
3) Connector reliability
4) Adversarial threats
5) Fuel demand
6) Location of refueling nodes ashore

Analytical Tools

The mathematical approach used during this analysis was generated by MATLAB, a modeling and simulation tool, to provide an optimized network of various fuel nodes. Fuel was delivered via various methods to include air (i.e. CH-53 E/K, MV-22), surface (i.e. LCAC/SSC, LCU-1600/1700), and ground (i.e. MTVR, LVSR). Given the scenario, the optimized solution to deliver fuel was based on varying factors such as quantity of delivery methods available, threat against air and surface delivery methods, weather, maintenance reliability, and cost per hour of operation for the available fuel delivery options.

Conclusions

Surface connectors are the primary means of fuel delivery from the ship to the shore. They provide the largest delivery capacity, but are limited by speed and access to inland nodes.

Air connectors provide an additional means of delivery to meet demand and reach inland nodes. They have greater speed and reach than surface connectors, but are limited by capacity. The number of air sorties increase as Ship-to-Shore (STS) distance and surface connectors are impacted by threat and weather.

An unplanned benefit of this study was that this network planning tool could be useful for MAGTF planners to develop estimates of supportability for future operations. This tool can aid in determining equipment shortfalls, fuel choke points, and sortie requirements.

Introduction

There are an increasing number of countries that are obtaining or improving their Anti-Access/Area Denial (A2AD) capabilities. These are capabilities that seek to inhibit military movement into a theater or deny freedom of action within an area under the enemy's control. As enemy A2AD capabilities increase, so does the distance from which supporting units must operate.

As a force in readiness and often referred to as America's 911 Force, the Marine Corps is forward deployed 24 hours a day, 7 days a week. Forward deployments occur in various forms of the Marine Air Ground Task Force (MAGTF), but the most common is the Marine Expeditionary Unit (MEU). MEUs are typically embarked on three Navy amphibious ships which are referred to as an Amphibious Ready Group (ARG). When a MEU moves from the ship to the shore during contingency operations, the MEU is still heavily reliant on the ARG for logistics to include fuel supply. The farther from shore the ARG is, the more strained the logistics of moving supplies ashore becomes. In an A2AD environment, that logistical strain to deliver the right amount of fuel at the right place and time is increased because the ARG is further from the shore (approximately 8-12 nautical miles (nm)) than they would be if not in an A2AD environment. This study analyzed the various impacts of delivering fuel to the shore based on delivery method, threat and weather impacts, equipment maintenance reliability, and distance while comparing those variables to cost.

Assumptions and Limitations

The underlying assumption for this study is that conditions are set such that fuel delivery from the ship to the shore is readily available. Additionally, the enemy threat is minimized to the point that surface and air connectors can deliver fuel in a semi-permissive environment, such that friendly forces have local air and maritime superiority while encountering a minimal enemy threat.

To provide a sense of realism to the study while remaining unclassified, a number of assumptions were made to determine notional threat levels and their relative impact to air and surface connectors when delivering fuel, as shown in Tables 1 and 2 below. Three threat levels were developed: low, medium, and high for both surface and air connectors. The "X" in the respective threat level column denotes whether the threat level possibly contains that specific threat. For example, in the Medium Surface Threats depicted in Table 1, there is a possible guided mortar, mine, or small boat threat. However, there is not a possible threat of mobile Coastal Defense Cruise Missiles (CDCMs) or Anti-Tank Guided Missiles (ATGMs). Likewise, in Table 2, there is a 10% chance that a low air threat would impact the air connectors' ability to deliver fuel due to a rocket propelled grenade (RPG) or small arms threat. Although important to the validity of the information obtained by this study, the threat levels are not the main focus.

Surface Threats	Low	Med	High
Mobile CDCMs			x
ATGMs			x
Guided Mortars		x	x
Mines (sea)	x	x	x
Small Boats		x	x
Probability Threat Impacts Surface Connectors	5%	10%	15%

Table 1: Threat Impacts to Surface Connectors

Air Threats	Low	Med	High
RPGs	x	x	x
Mobile SAMs			x
Manpads		x	x
Small Arms	x	x	x
Probability Threat Impacts Air Connectors	10%	20%	30%

Table 2: Threat Impacts to Air Connectors

Notional weather conditions were also developed to provide another aspect of realism to the study. Three types of weather conditions; A, B, and C; were used to determine the impact weather would have on availability of connectors. Weather Condition A was determined as the ideal condition such that there is a 5% chance of likelihood that weather would adversely impact either surface or air connectors, thus making them unavailable for use. Weather Condition B impacted air connectors more so than surface connectors, 40% chance of an impact to air compared to 5% chance of an impact to surface connectors, due to having less than one (1) mile of visibility. Conversely, Weather Condition C impacts surface connectors, 30% compared to a 5% chance of an impact to air, due to a sea state of four (4) or greater. Table 3 identifies the weather conditions and respective likelihoods of impact.

Environmental Conditions	A	B	C
Wind	<30kts	<30kts	<30kts
Sea-State	0-3	0-3	**4+**
Precipitation	<.3 in/hr	<.3 in/hr	<.3 in/hr
Cloud Layer	>500 ft	<500 ft	>500 ft
Visibility	>1 mi	**<1 mi**	>1 mi
Probability of impacting Surface Operations	5%	5%	30%
Probability of impacting Air Operations	5%	40%	5%

Table 3: Environmental Impacts to Air and Surface Connectors

To develop the potential overall impact threat and weather have on the connectors and assuming the two are independent of one another, the following formula was used:

$$1 - ((1 - probability\ of\ threat) * (1 - probability\ of\ weather)).$$

As an example, the probability of unavailable surface connectors due to independent variables low surface threat and Weather Condition A, are:

1-((1-0.05)*(1-0.05)) =
1-(0.95*0.95)=
0.0975 or 9.75%.

Due to the A2AD nature of the operational scenario of this study, there was an assumption that in a low threat environment, the ships operated 8 nm off the shore. In a medium and high threat environment, this study assumed the ships were 12 nm off the shoreline due to the increase in threat. These two factors were considered in the model as a time-distance factor and potentially limited the number of sorties available during a 24-hour period of time.

Additionally, this study used currently approved programs of record to determine the types of air, surface, and land connectors available, and the fuel demand ashore represented a steady-state support requirement.

Analytical Approach

The objective of this study was to analyze multiple mixes of air and surface connectors to deliver fuel ashore to meet the demand of a MEU operating within an A2AD environment in order to determine the best use of the connectors at various threat levels.

The factors involved in determining the best mix of air and surface connectors were:

- Sea state and weather
- Stand-off distance due to adversary threat capabilities
- Connector speed, capacity, and readiness

Methodology

As depicted in Figure 1, the methodology used to determine the study results were based on the 2015 MEU Equipment Density List (EDL) and availability of various connectors. These included the LCAC/SSC and the LCU as surface connectors, the CH-53E/K and the MV-22 as air connectors, and the MTVR and LVSR as land connectors. Fuel demand ashore was obtained from the MAGTF Planner's Reference Manual. The various threats and weather conditions, displayed in Tables 1 through 3, developed the scenarios. By combining the fuel demand ashore, 20,000 gallons per day, and the scenarios, the operational concepts were developed which, when ran through the model, provided outputs on the transportation cost of fuel, amount of fuel delivered, and connector usage.

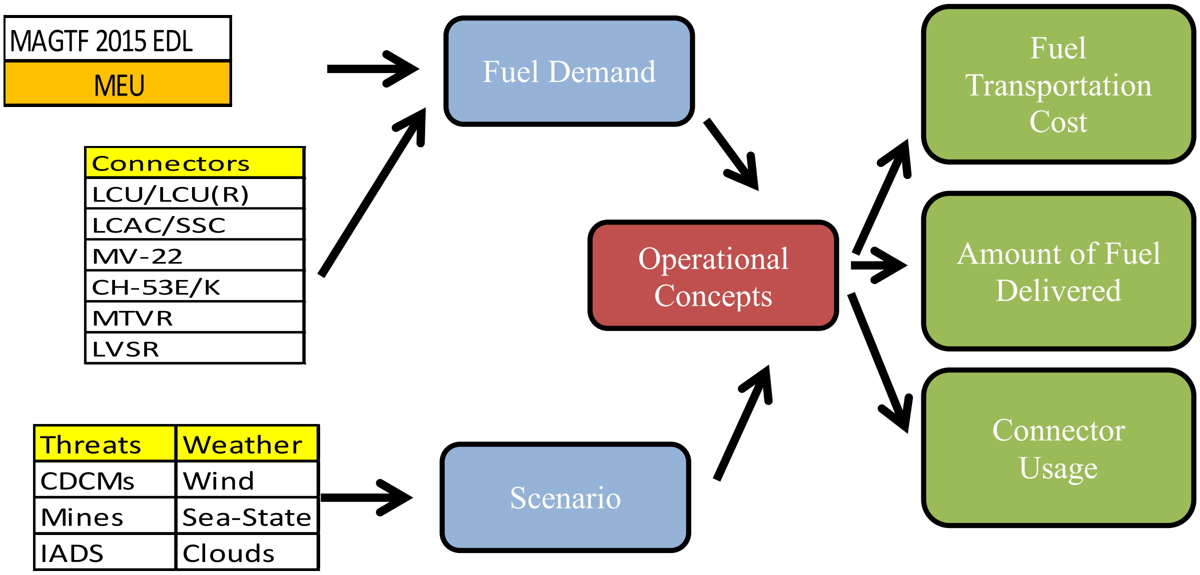

Figure 1: Methodology

As connectors are not solely used to deliver fuel, this study varied the quantity of air and surface connector sorties available to four basic scenarios taking into account current and future MEU connectors. The "100% of Air/Surface Available" scenario has four LCU-1600/1700, ten LCAC/SSC, six CH-53E/K, and twenty-four MV-22B sorties available. A second scenario was the "50% of Air/Surface Available" which had two LCU-1600/1700, five LCAC/SSC, four CH-53E/K, and twelve MV-22B sorties available. An "Air Heavy" scenario was used in the event a low number of surface connector sorties were available for fuel delivery. The quantity of connector sorties for this scenario was one LCU-1600/1700, two LCAC/SSC, six CH-53E/K, and twenty-four MV-22B sorties. Conversely, a "Surface Heavy" scenario was developed using four LCU-1600/1700, ten LCAC/SSC, two CH-53E/K, and six MV-22B sorties. Table 4 shows the four base scenarios and the respective quantities of connector sorties available for each scenario.

	Number of Sorties – Current MEU/Future MEU			
Base Scenario	**LCU-1600/ LCU-1700**	**LCAC/SSC**	**CH-53E/ CH-53K**	**MV-22B**
100% of Air/Surface Available	4	10	6	24
50% of Air/Surface Available	2	5	4	12
Air Heavy	1	2	6	24
Surface Heavy	4	10	2	6

Table 4: Base Scenarios

Based on the four scenarios identified in Table 4 and the threat and weather impacts displayed in Tables 1 through 3, thirty-six scenarios were generated for current MEU connectors and thirty-six scenarios were developed for future MEU connectors. This equates to seventy-two total scenarios. As a function of sensitivity analysis, additional attributes were used such as operational availability of connectors where equipment readiness was based off a mean average of FY15 readiness for the respective connectors. Where readiness numbers were unavailable, such as the future MEU scenarios, the program of record threshold requirement for connector availability, depicted in the requirements document for those assets, was used. To assess the sensitivity of the model, 1000 runs were conducted per scenario to determine the results.

The study supposed MEU level operations ashore involving four beach nodes and three inland nodes. In this scenario, there are two beach nodes that are accessible by surface connectors, two inland nodes that are accessible by air connectors, and three inland nodes that are only accessible by land connectors. Also assumed, there was a Forward Arming and Refueling Point (FARP) for attack helicopters at Beach Node 4. Figure 2 below shows the layout of the nodes ashore, the distance between them in nautical miles (nm), and direction of fuel flow via land vehicles. Table 5 displays the daily fuel demand at each node and what connectors were able to deliver fuel to those nodes.

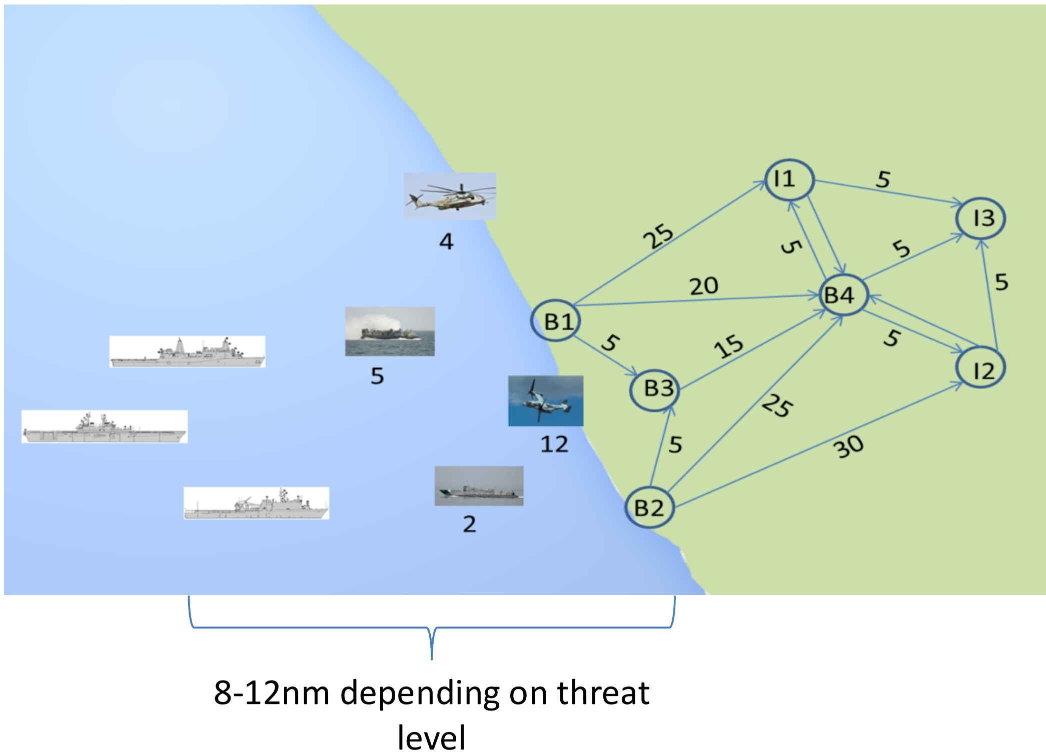

Figure 2: Nodal Network

Node	Fuel Demand in Gal/Day	Connectors
B1	500	Surface/Air
B2	500	Surface
B3	1,000	Air/Land
B4	13,000	Air/Land
I1	1,500	Land
I2	1,500	Land
I3	2,000	Land

Table 5: Fuel Demand per Node

MATLAB Model

The MATLAB model used in this analysis was developed by Dr. Michael Atkinson and Dr. Kyle Lin of the Operations Research Department at the Naval Postgraduate School in Monterey, California. This model used linear programing to mathematically depict the fuel demands in the form of an optimized network flow model and represented a 24-hour period of fuel delivery operations. This network flow problem was represented by a collection of supply, demand, and transshipment nodes which were connected through edges or arcs. These arcs indicated valid paths or links between nodes that were used and typically constrained to the maximum number of items that could move along them. The goal of this network flow model was to determine how many items could be moved through the arcs to meet demand. Since there was usually a cost associated with the movement of the item, the network flow model was made to minimize these costs. This is known as a minimum cost network flow problem. The objective function and constraints are listed below using NPS standard form notation[i].

$$\min_{x_{ij}} \quad \sum_{(i,j)\text{ edges}} c_{ij} x_{ij}$$

$$\text{subject to} \quad \sum_{j:(k,j)\text{ edge}} x_{kj} - \sum_{i:(i,k)\text{ edge}} x_{ik} = b_k \quad \text{for all nodes } k$$

$$0 \le x_{ij} \le u_{ij} \quad \text{for all } (i,j) \text{ edges}$$

The objective function of the MATLAB network flow model was to minimize the total transportation cost (c_{ij}) to push fuel through the system edges which included the cost to transport or move fuel. While concrete monetary transportation costs are important, the model was constructed such that certain c_{ij} represent important, albeit less concrete, costs such as the cost of unmet demand and the cost of idle/unused connectors. The first constraint of the model was that for each node the difference between the fuel flow into the node and the flow out of the node must equal the demand (b_k) at that node. For instance, if a node requires 500 gallons of fuel, then a feasible solution would ship 1,500 gallons into the node and 1,000 gallons out of the node to other locations. The second constraint is that the fuel flow along an edge must be greater than or equal to zero and less than or equal to the capacity at that edge. For this study, capacity represents how much fuel can be pushed along a road in a 24-hour period, availability of land connectors, speed of land connectors along the road, and distance.

When solved, the model returned the assignment of each connector to a delivery node, flow in gallons of fuel transported to that node, minimum cost to push fuel through the system, and the number of gallons of unmet demand.

To perform sensitivity analysis on this network flow model, the following data was collected:

- Connector Failure Rate - probability that the connector is unavailable for maintenance.
- Air Down - probability that threat or environment prevents use of air connectors
- Surface Down - probability that threat or environment prevents use of surface connectors
- Fuel Demand at Node - Variable amount (Low, Medium, High)
- Edge Availability - probability that road cannot be traversed for threat and weather or reliability associated with a land connector.

Surface Connector Data

An ARG is made up of three ships: an Amphibious Transport Dock (LPD), a Dock Landing Ship (LSD), and an Amphibious Assault Ship (LHD/LHA). The LPD, LSD, and LHD/LHA can carry a mix of LCU and LCAC type connectors. A current day ARG with a MEU embarked usually deploys with two LCU-1600s and five LCACs as their organic surface connectors. The surface connectors deliver vehicles and cargo from the ARG to the shore during amphibious operations. The future ARG/MEU will carry a mix of LCU-1700s and SSCs that will replace the LCU-1600s and LCACs with comparable capabilities.

The surface connectors can deliver fuel ashore in a variety of ways. The best option, considering time and effort, is to utilize vehicles capable of transporting bulk fuel to facilitate a faster rate of loading and unloading of the surface connectors. There are multiple vehicle options organic to the MEU: Medium Tactical Vehicle Replacements (MTVRs) or Logistics Vehicle System Replacements (LVSRs) with sixcons, LVSRs with a flatrack refueling system, or MTVRs with 500 gallon drop drums. The MTVRs with three drop drums allowed the most capacity of fuel to be delivered by all four of the surface connectors. The capacity of JP-5 per surface connector is listed in Table 6.

Connector Type	Connector	Fuel Deliverable (Gal JP-5)	Method
Surface	LCU-1600	6000	4 MTVRs w/3 drop drums each
Surface	LCAC	3000	2 MTVRs w/3 drop drums each
Surface	LCU-1700	6000	4 MTVRs w/3 drop drums each
Surface	SSC	3000	2 MTVRs w/3 drop drums each

Table 6: Surface Connector Fuel Delivery[1]

The cost to operate the surface connectors per hour was determined using the estimated Operating and Support costs from the SSC Selected Acquisition Report from March 2015 and from information contained in a Cost Benefit and Capability Analysis NPS Thesis by Justin Dowd in September 2009. The time to load and offload vehicles with bulk fuel for all four surface connectors is based on the planning factors for an LCAC from the MAGTF Planner's Reference Manual. The MAGTF Planner's Reference Manual also provided speeds at which the surface connectors could operate while ferrying vehicles ashore. Table 7 provides the speeds, cost per hour, and time delays that were utilized in this study.

Connector Type	Connector	Cost per Operational Hour ($ per hour)[2-3]	Speed (Kts)[1]	Time to load (Hrs)	Time to offload at Beach (Hrs)	Total Delay time

[1] MAGTF Planner's Reference Manual, MAGTF Staff Training Program (MSTP), U.S. Marine Corps, November 2012

						(Hrs)[1]
Surface	LCU-1600	$2,055	11	1	1.5	2.5
Surface	LCAC	$18,102	35	1	1.5	2.5
Surface	LCU-1700	$1,747	11	1	1.5	2.5
Surface	SSC	$14,096	35	1	1.5	2.5

Table 7: Surface Connector Attributes

Historical maintenance readiness for the surface connectors was not easily obtainable. Therefore, threshold requirements obtained from program documents for material availability was used for the SSC and draft requirements for LCU-1700. LCU-1600 and LCAC historic threshold program requirements for material availability were assumed to be identical to that of the systems replacing them, LCU-1700 and SSC, respectively. Table 8 below displays the connector reliability assumed for this study.

Though programs' material availability degrades over the years, equipment forward deployed on an ARG/MEU has priority on supply of part requests over most equipment in CONUS to maintain the equipment in operational condition.

Surface Connector	Reliability (Threshold Requirements)
LCU-1600	0.90
LCAC	0.85
LCU-1700	0.90
SSC	0.85

Table 8: Surface Connector Reliability

Air Connector Data

The Aviation Combat Element (ACE) provides the MEU with organic air support with fixed wing, helicopters, tiltrotor and UAV aircraft. In the current MEU construct, Close Air Support (CAS) is provided by AV-8Bs, AH-1Zs, UH-1Ys and combat assault transport for troop's supplies and equipment is provided by the MV-22B and CH-53E. The core of the ACE is the Marine Medium Tiltrotor Squadron (VMM) with twelve MV-22Bs. They are then reinforced by a select number of the other aircraft to form the ACE. Included in Table 9 for reference, but not in the analysis, are the KC-130J Cargo and Refueler variants. The KC-130J was not included in the analysis because it would not be available or have a place to land in an A2AD environment. Of note, the KC-130J would significantly impact the analysis because of the large volume of fuel this aircraft can carry at a much lower cost than the other air connectors.

[2] Selected Acquisition Report (SAR): Ship to Shore Connector Amphibious Craft (SSC); As of FY 2016 President's Budget, March 18, 2015
[3] Dowd, Justin A. Naval Postgraduate School Thesis: Cost Benefit and Capability Analysis of Seabase Connectors, September 2009

Connector Type	T/M/S	Fuel Deliverable (Gal JP-5)	Method	Fuel on/off load JP-5 (gal / min)
Air Vehicle	CH-53E	2,200	ADGR TBFDS	74
Air Vehicle	CH-53K	2,200	ADGR TBFDS	74
Air Vehicle	MV-22B	1,175	ADGR MATS	59
Air Vehicle	KC-130J	4,400 (6-hr Round Trip)	Cargo Configuration	110
Air Vehicle	KC-130J	7,500 (6-hr Round Trip)	Tanker Configuration	110

Table 9: Air Vehicle Fuel Delivery[4]

The primary method of fuel delivery for each aircraft is the use of internal storage. Each connector will utilize Aviation Delivered Ground Refueling (ADGR) to bring fuel ashore. The CH-53 will utilize the Tactical Bulk Fuel Delivery System (TBFDS) and the MV-22B will use internal fuel stores augmented with the Mission Auxiliary Tank System (MATS). The capacity of JP-5 is listed in Table 9. External operations were not considered because the aircraft are operating in an A2AD environment. It was assumed that the off-load site would be safer than the flight to the node, and by using only internal transport methods, the aircraft would be able to maneuver against threats and the MV-22 could take advantage of its speed.

Cost to operate per flight hour was determined using type/model/series (T/M/S) specific SARs and then converting to FY16 base year dollars. The time to offload fuel is based on the planning factors from the Tactical Pocket Guide for each T/M/S. Based on these factors, it was possible to determine the total time delay for fuel off-load at the destination node. All air connector attributes are listed in Table 10.

Connector Type	T/M/S	Flight Hour Operational Cost ($ per flight hour)	Speed (Kts) Max Range	Time to offload (Hrs)	Time to setup/tear down (Hrs)	Node Delay time (Hrs)
Air Vehicle	CH-53E	$26,680	130	0.50	0.25	0.75
Air Vehicle	CH-53K	$35,552	140	0.50	0.25	0.75
Air Vehicle	MV-22B	$20,207	215	0.33	0.53	0.87
Air Vehicle	KC-130J	-	290	0.67	0.25	0.92
Air Vehicle	KC-130J	-	290	1.14	0.25	1.39

Table 10: Air Connector Attributes[4]

It was found that there are many metrics by which Marine Aviation measures aircraft readiness, and that the metric used most often depended on what question you were trying to answer. One method is to determine the minimum aircraft readiness required to

[4] Assault Support Tactical Standard Operating Procedures (ASTACSOP), NTTP 3-22.5-ASTACSOP, June 2014

support an average T/M/S T-Rating of 2.0 derived from all fleet squadrons' reported T-Levels. T-Rating is one of the primary assessment metrics for Naval Aviation Enterprise (NAE) to determine whether squadrons have the resources required to generate readiness. A T-Rating is a metric used to determine if a squadron is properly resourced with the correct number of personnel, aircraft and parts. This scale measures from 1.0 to 4.0 with T-2.0 being the goal set for every aviation unit by the Deputy Commandant for Aviation (DCA) in the 2015 Aviation Plan (AVPLAN). To measure the threshold readiness required for T-2.0, divide Ready Base Aircraft (RBA) by the Flight Line Entitlement (FLE) as a measure of minimum squadron reliability[5]. RBA is the number of aircraft required in an up or flyable status for a properly-resourced squadron to maintain a ready to deploy posture. For example, the CH-53E needs a readiness average of 62% to maintain T-2.0 with a FLE of 13 aircraft which results in a requirement to have eight up aircraft each day.

T/M/S	FLE per Squadron	RBA Required for T-2.0	Reliability Required for T-2.0	Reliability (Fleet Unit Average)
CH-53E	13	8	0.62	0.46
CH-53K	13	8	0.62	0.58
MV-22B	12	7	0.58	0.50
KC-130J	15	9	0.60	0.59
KC-130J	15	9	0.60	0.59

Table 11: Air Connector Reliability[6]

Another way to measure readiness, and ultimately the method selected, is to take the total number of operational fleet aircraft in an "up" status and divide by the total number of aircraft reporting. Table 11 above displays the aircraft reliability percentages used in this study. The limitation is that the data is a "snap-shot in time" and represents the current fleet average as measured that day. This data was collected from the DCA Readiness Brief dated 26 July 2016 and has removed the data from training and non-deployable squadrons. Additionally, the data does not reflect the higher priority for parts that deployed squadrons receive. These numbers are more representative of a "come as you are" and "fight tonight" readiness posture.

Measures of Effectiveness

This study used the following Measures of Effectiveness to meet the study objective:

1. Unmet fuel demand in gallons per day
2. Connector utilization per number of sorties
3. Cost of transporting 1 gallon of fuel

Study Results

[5] Aircraft Maintenance Training and Readiness (T&R) Program (AMTRP), 2 October 2009

[6] Marine Aviation Plan 2015; DCA Readiness Brief

The study utilized normal air and surface connector loadouts for a current ARG/MEU to develop four base scenarios by varying the number of air and surface connector sorties available for fuel delivery, as previously depicted in Table 4. The same logic was applied to future air and surface connector options to define four base scenarios for a future ARG/MEU.

As previously discussed in section "Methodology" of this report, thirty-six scenarios were developed from the four base scenarios for a current ARG/MEU and thirty-six scenarios were developed for a future ARG/MEU based on a combination of threat levels and environmental conditions.

Base Case: Ideal Conditions

The results of the first part of the study concentrated on the optimization of the flow of fuel ashore with the lowest cost. The initial optimization results were developed under what was considered perfect conditions; where the optimization model did not take into account the threat, environmental, and connector reliability probabilities. The MATLAB optimization program utilized the connector cost per gallon of fuel delivered to develop an optimized solution to meet the fuel demand ashore at the lowest cost. Therefore, most of the results were very similar to one another. The major differences between the results were due to the different connector attributes associated with the current and future ARG/MEUs, as well as differences between each scenario's off-shore distance due to the changes in threat levels.

The optimization model's results of delivering fuel ashore revealed that all seventy-two scenarios were able to deliver enough fuel ashore to meet the daily demand under perfect conditions. These initial optimization results also yielded some insights into costs of delivering fuel ashore as well as connector utilization. Figure 3 displays the optimized results of the base scenarios' range of transportation cost per gallon of fuel delivered ashore for all seventy-two scenarios. The x-axis of Figure 3 represents the four base scenarios with the y-axis representing the cost per gallon. The range bars include data for eighteen scenarios each that display the range of the cost per gallon by base scenario. The main insight from the range of the results of the "Air Heavy" base scenarios across the different scenario combinations indicate that there is a significant cost increase when relying on air connectors to deliver fuel compared to surface connectors.

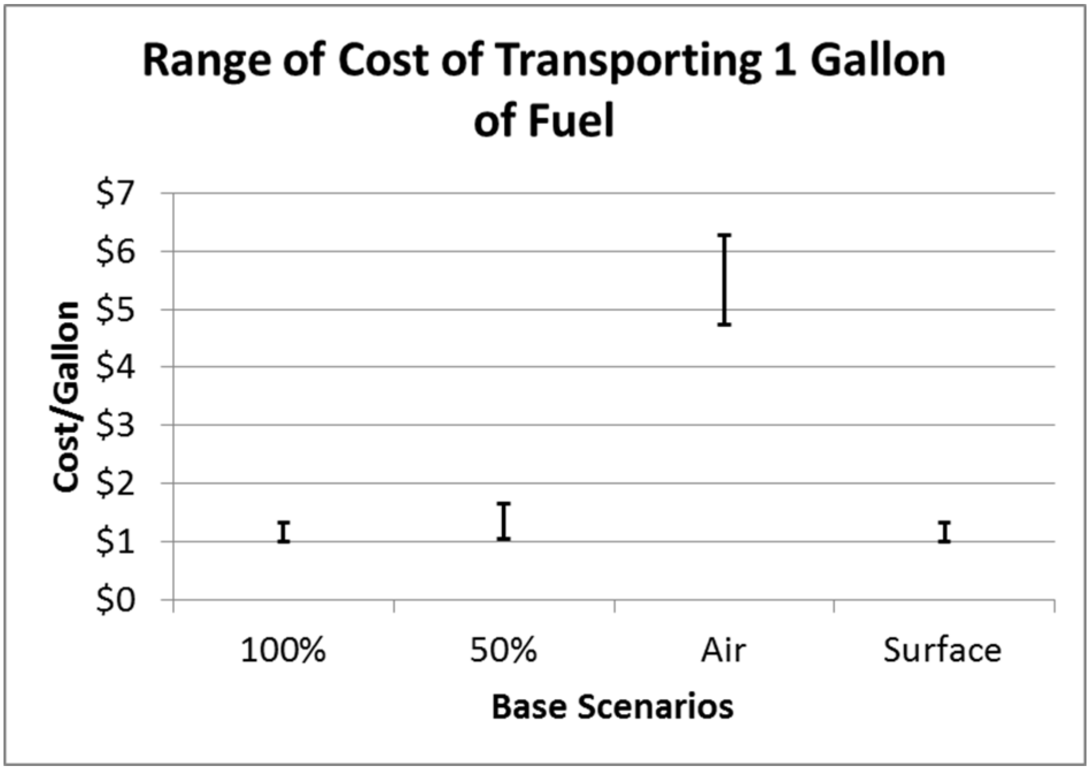

Figure 3: Range of Transportation Cost per Gallon of Fuel Delivered

The optimization model's results of connector sortie execution revealed two insights: (1) The surface connectors were heavily favored across the base scenarios for their low transportation costs per gallon of fuel delivered ashore. (2) The only time air connectors were utilized was during the "Air Heavy" base scenarios; however MV-22Bs were not used throughout the seventy-two scenarios due to their high transportation costs per gallon of fuel delivered.

Figure 4 displays the range of results of air and surface connector utilization by base scenario for the thirty-six scenarios representing the connectors of a current ARG/MEU. The x-axis of figure 4 represents the four base scenarios with the y-axis representing the number of sorties. The base scenarios, along the x-axis, include data for nine scenarios each with the number of sorties of the four connectors displayed in each column. The only connector where the number of sorties results varied between scenarios was that of the LCAC. All the other connectors maintained the number of sorties shown below for each variation of the base scenario.

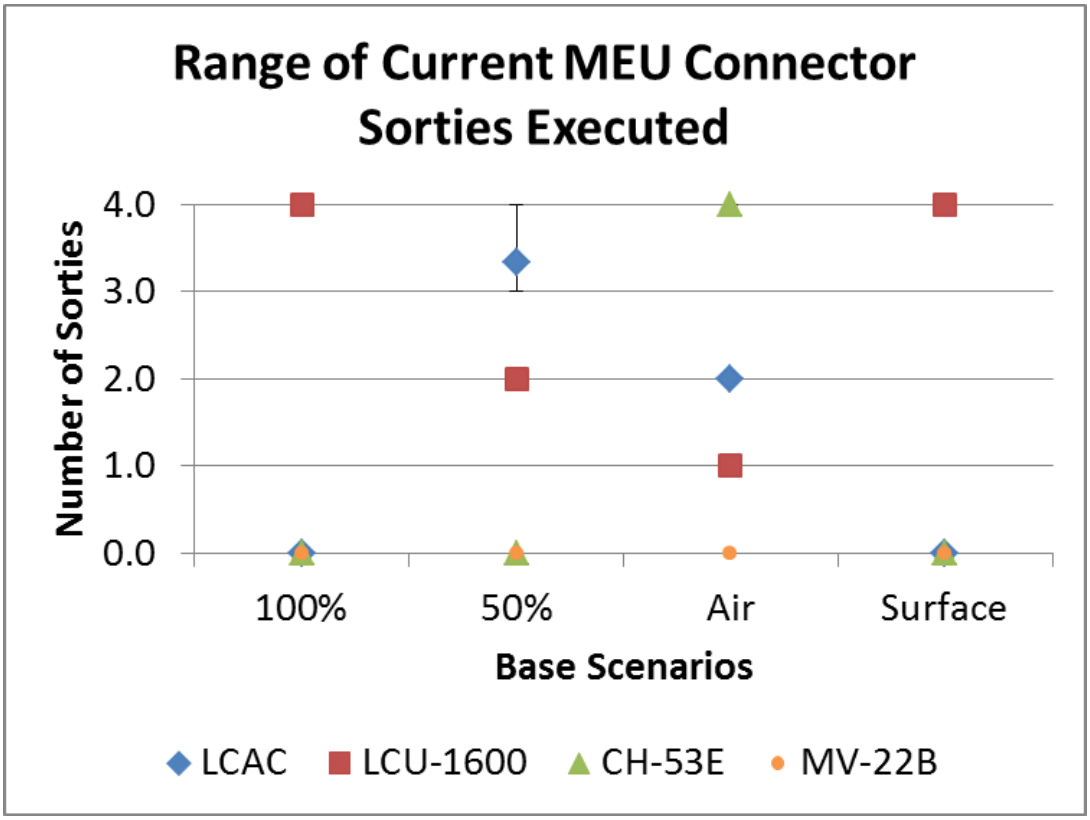

Figure 4: Range of Connector Utilization by Base Scenario

Sensitivity Analysis

The second part of the study incorporated the threat, environmental, and connector reliability probabilities for sensitivity analysis of the seventy-two scenarios. A separate MATLAB model was utilized to explore the sensitivity of the ability of the scenarios to meet demand over 1000 runs. The model used the input probabilities for the level of threat, as shown in Tables 1 & 2, the type of environmental impacts, as shown in Table 3, and the reliability of the connectors to randomly cause failures while trying to meet demand at the lowest cost.

Since it is vital Marine Forces ashore have sufficient fuel supplies to maintain operations, the impacts of the threat, environment, and connector reliability probabilities had on meeting daily fuel demand was the focus of effort.

To baseline the sensitivity analysis of meeting fuel demand ashore, the amount of unmet demand in a low threat, minimal environmental impact was reviewed. Figure 5 shows the range of unmet demand for 1000 runs of the model for the four base scenarios of a current day ARG/MEU. The x-axis of the following Figures 5 through 9 are the four different base scenarios, the left y-axis represents the number of gallons of unmet demand of fuel, and the right y-axis represents the percent of unmet fuel demand. The green box plots represent the range of the sensitivity results where the top of the green box represents the 75th percentile of the results. In other words, 75%

of the results lie at or below the top of the green box. The black line in the middle of the green boxes represents the median or 50th percentile. The top of the whisker that extends from the top of the green box represents the 90th percentile. The red diamond on the figure represents the mean average of the results. The four base scenarios show a very similar amount of risk of not meeting the fuel demand ashore in these conditions. The scenarios ran with the connectors envisioned for future ARG/MEUs showed similar results in all cases moving forward regardless of threat or environmental conditions.

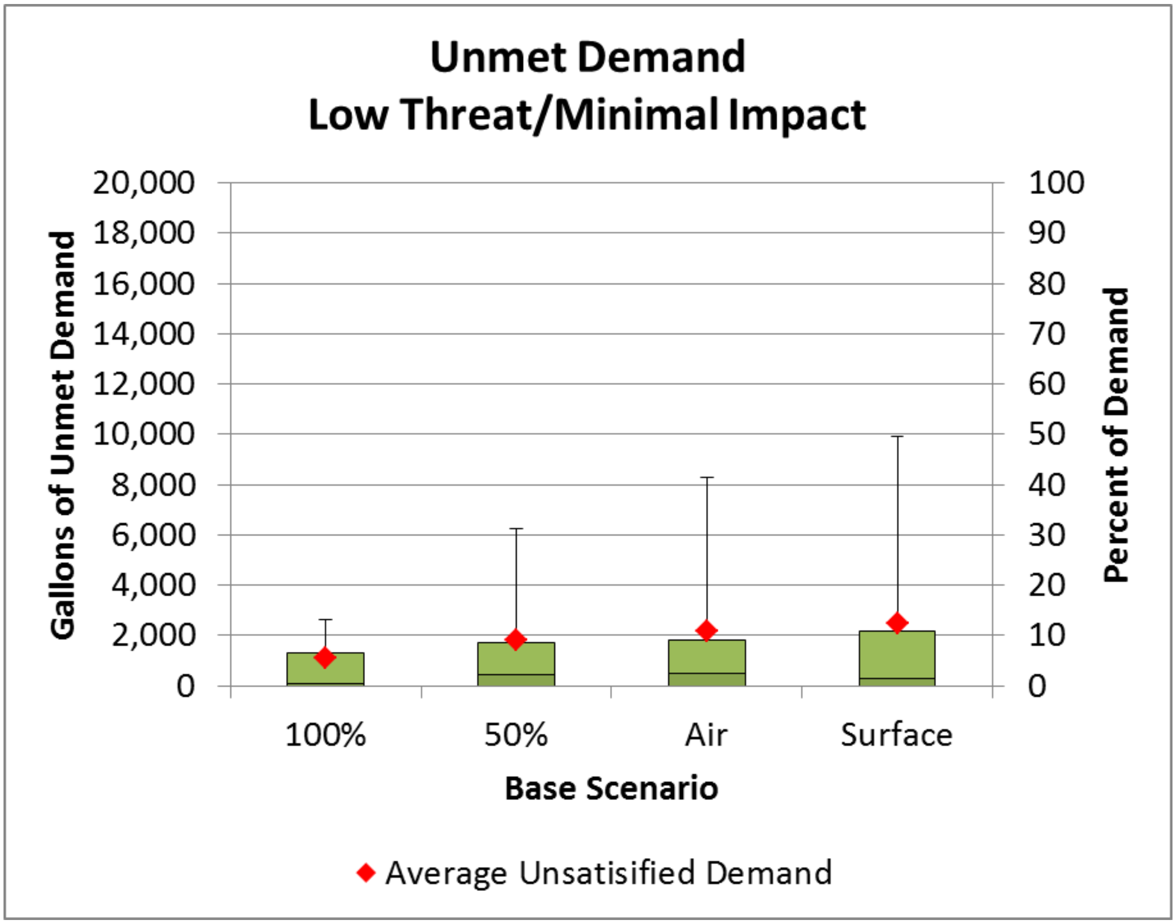

Figure 5: Unmet Demand - Low Threat, Minimal Environmental Impacts

After reviewing the amount of unmet fuel demand, several key insights resulted from the sensitivity. The first was that as the threat level, environmental conditions, and connector reliability limited the availability of the surface connectors, the risk of not meeting fuel demand increased. Figure 6 shows the range of unmet demand for 1000 runs of the model for the four base scenarios, with the connectors of a current day ARG/MEU, in a medium threat level and minimal environmental impact condition. The "Air Heavy" base scenario had significantly higher risk in meeting demand due to the low number of surface connector sorties allocated for fuel delivery. The trend of reliance on surface connectors to meet demand starts here due to the increase in threat. As the threat continues to increase, as well as changes in environmental impacts, the reliance on surface connectors becomes more apparent in Figures 7-8.

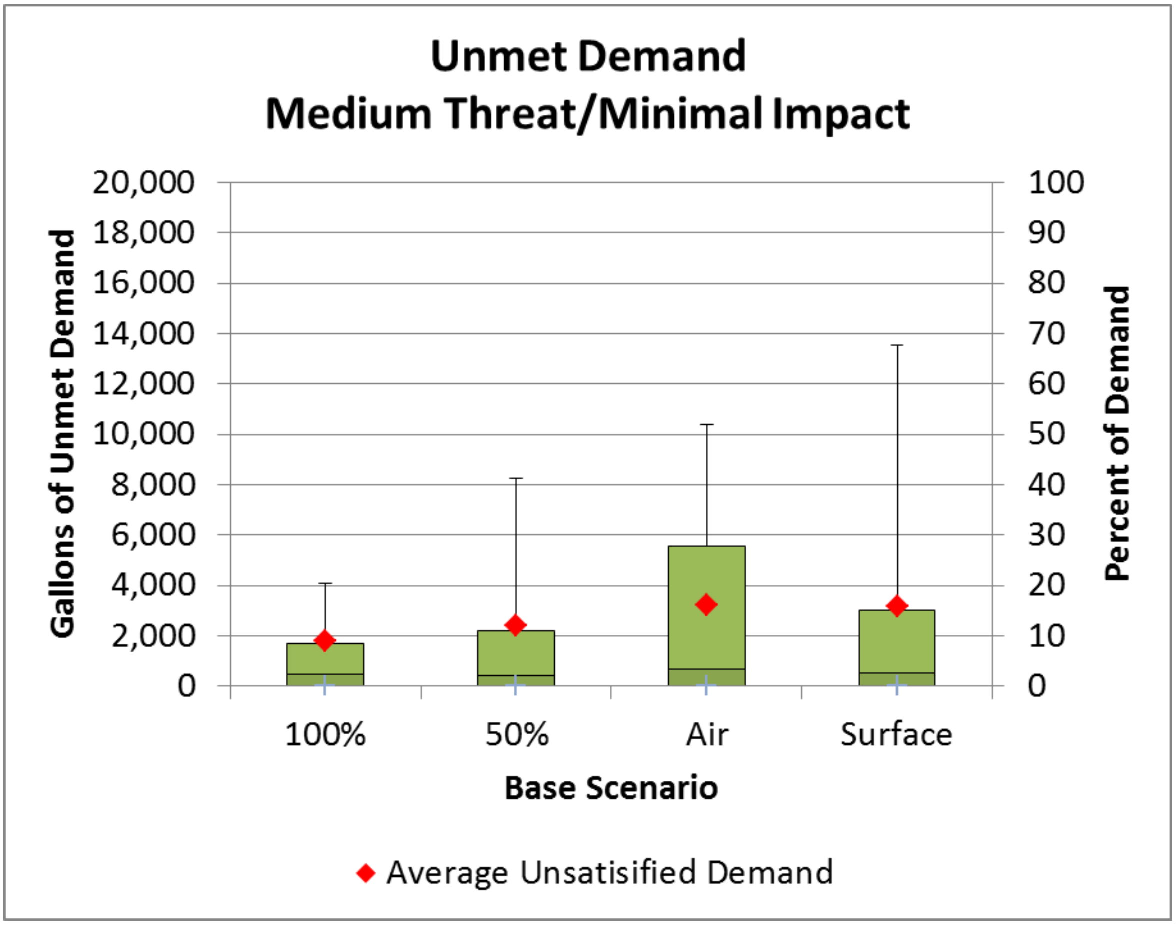

Figure 6: Unmet Demand - Medium Threat, Minimal Environmental Impacts

A second insight was that as the air connectors were impacted by environmental conditions, the risk of not meeting the fuel demand increased based on the quantity of air sorties available to offset the impacted surface connectors. Figure 7 shows the range of unmet demand for 1000 runs of the model of a current day ARG/MEU in the four base scenarios, in a medium threat level and an environmental condition that impacts the air connectors. Again, the "Air Heavy" base scenario had significantly more risk in not meeting demand due to the impact of the environment on the air connectors and the low number of surface connector sorties allocated for fuel delivery. The other base scenarios also show a risk increase of not meeting the fuel demand ashore, when compared to Figure 6, due to the availability of air connector sorties needed to supplement the loss of surface connector sorties.

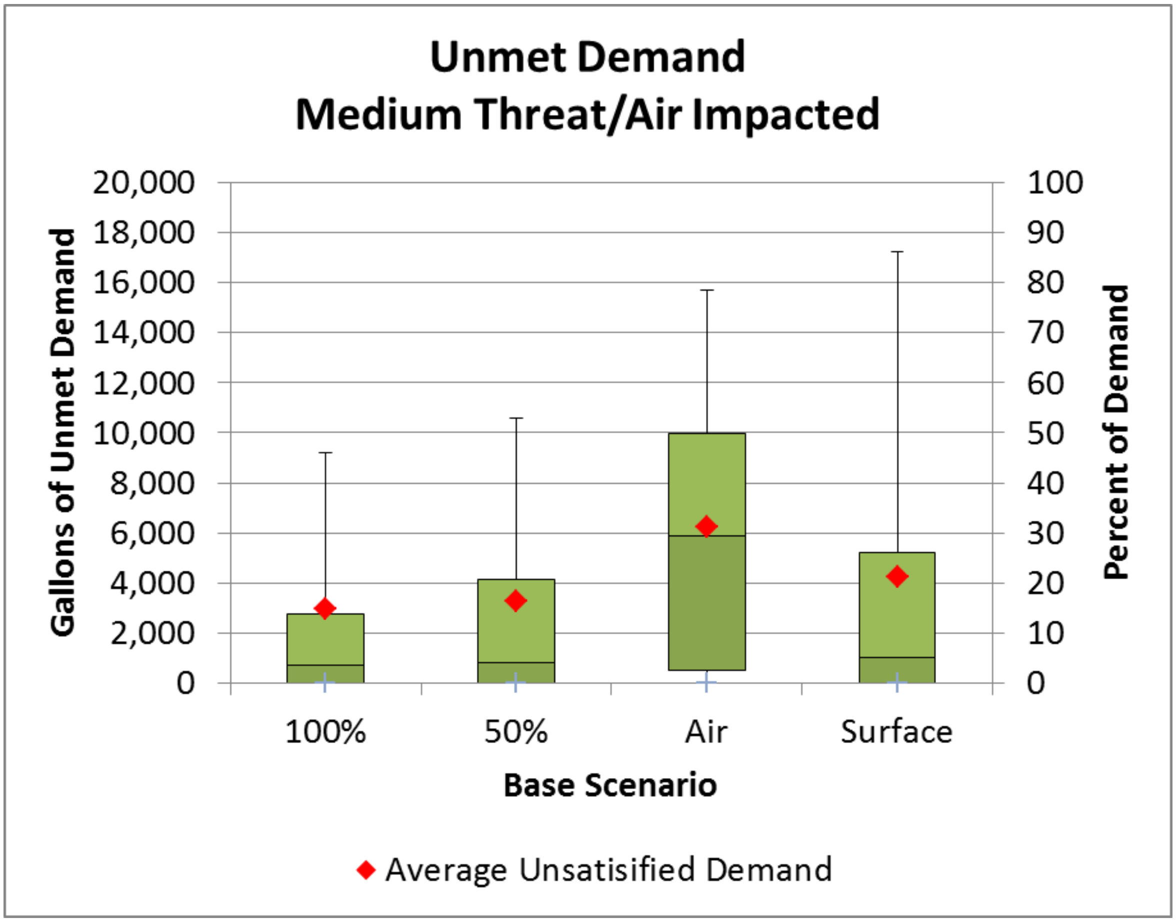

Figure 7: Unmet Demand - Medium Threat, Air Impacted Environment

A third insight related to meeting demand was that as the surface connectors were impacted by environmental conditions, the risk of air connectors alone not meeting fuel demand greatly increased. Figure 8 shows the range of unmet demand for 1000 runs of the model for the four base scenarios, with the connectors of a current day ARG/MEU, in a medium threat level and an environmental condition that impacts the surface connectors.

The scenarios displayed in Figure 8 had significant increases in risk of not meeting the fuel demand ashore due to the loss of surface connectors. The “50%” air and surface sortie availability and the “Surface Heavy” scenarios had the greatest increase in risk of not meeting the fuel demand, when compared to Figures 5-7, due to the loss of surface connector sorties available and the insufficient number of air connector sorties. Additionally, the “Air Heavy” scenario still shows a significant amount of risk of not meeting the fuel demand ashore which identifies the reliance of surface connectors needed for fuel delivery.

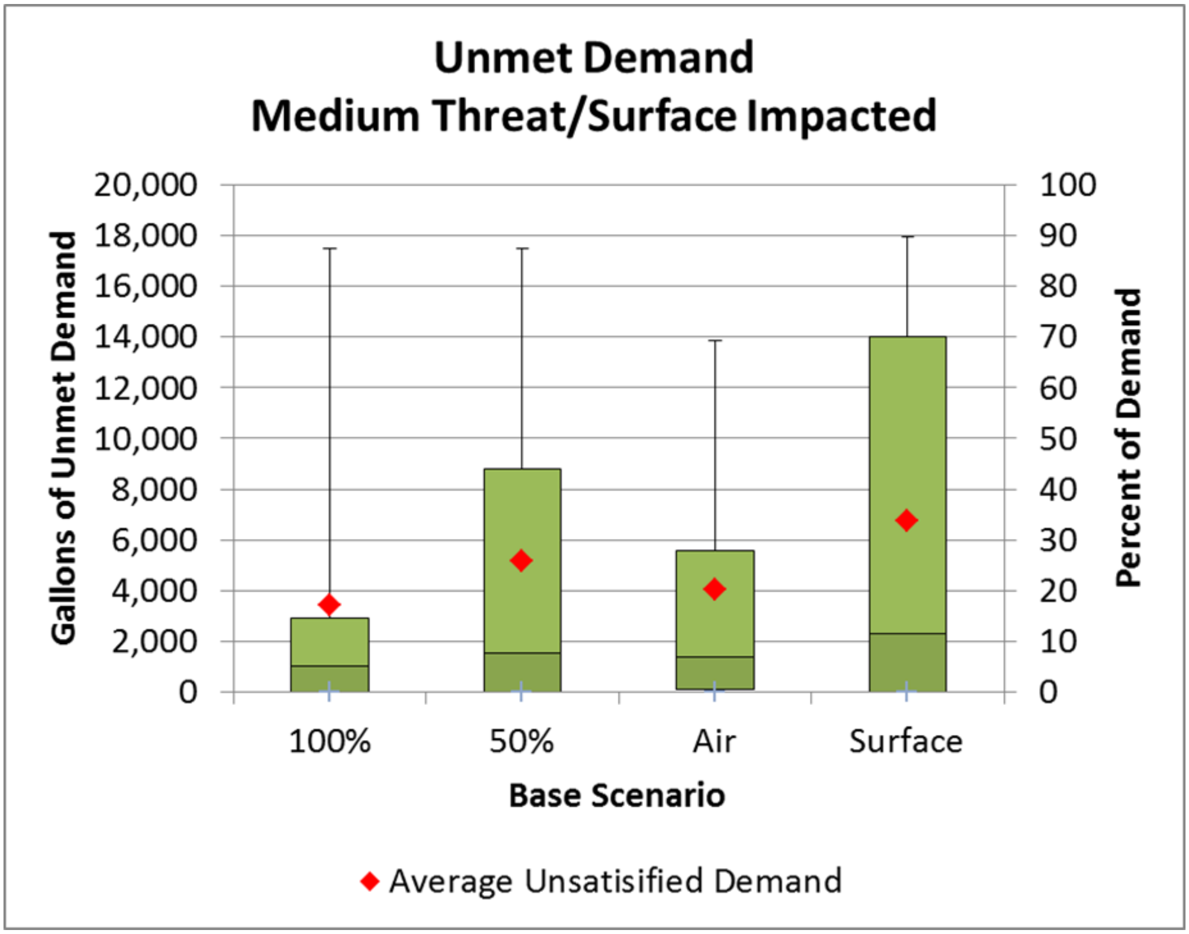

Figure 8: Unmet Demand - Medium Threat, Surface Impacted Environment

The fourth insight and as expected, as the threat level increased from low to high, the risk of not meeting the fuel demand ashore increased. Figure 9 shows the range of unmet demand for 1000 runs of the model for the “Air Heavy” scenario, with the connectors of a current day ARG/MEU, in a minimal impact environmental condition across the three threat levels. Although the results of the “Air Heavy” scenarios are shown, the other base scenarios (100%, 50%, and Surface) had comparatively similar results.

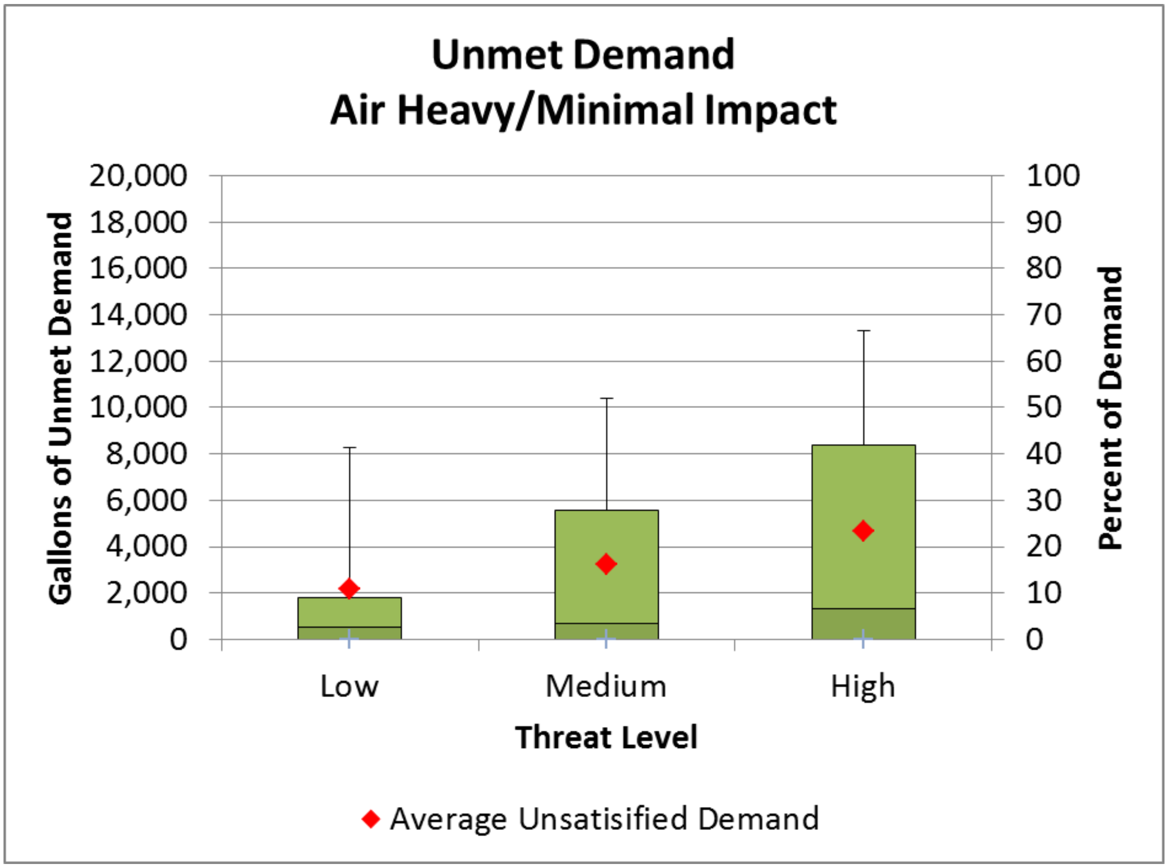

Figure 9: Unmet Demand - "Air Heavy" Scenarios by Threat Condition, Minimal Environmental Impact

Time as Cost: Preliminary Results

During operations, a commander is agnostic of monetary cost associated with the transportation of fuel, but more concerned about the time associated with meeting demand. An approach to this situation that was briefly explored late in this study was the concept that time is money. The approach explored altered the current method of determining cost utilizing a mathematical method known as feature scaling. Feature scaling is a technique used to standardize a range of independent variables or features of data. Since the range of values of raw data varies widely, objective functions will not work properly without normalization. If one of the features has a broad range of values, the variability is governed by this particular feature. Therefore, the range of all features is normalized so that each feature contributes approximate proportionately to the final variability[7, 8]. It is important to note that the following work is preliminary analysis of the results obtained via feature scaling, and that further in-depth analysis is required to

[7] Aksoy, S. and R. Haralick, "Feature normalization and likelihood-based similarity measures for image retrieval," Pattern Recognition. Special Issue on Image and Video Retrieval, 2000, pages 1-4. http://www.cs.washington.edu/homes/lfb/paper/nc06.pdf last accessed 24 September 2016.

[8] Bin Mohammad, Ismail; Dauda Usman (2013). "Standardization and Its Effects on K-Means Clustering Algorithm". Research Journal of Applied Sciences, Engineering and Technology, pages 3299, 3300. http://maxwellsci.com/print/rjaset/v6-3299-3303.pdf last accessed 24 September 2016. http://www.cs.washington.edu/homes/lfb/paper/nc06.pdf last accessed 24 September 2016.

prove the validity of this approach. It is also possible that other alternatives to representing Time as Cost may exist.

To perform normalization of the data, first rank the variables on a scale from one to seven for each connector attribute, where one is the best and seven is the worst. The following three attributes were used to calculate their average rank as depicted in Table 12.[9]

1. Rank of Time it takes the connector to reach each location
2. Rank of Time associated with connector delays to offload fuel
3. Average Rank of Speed at which the connector travels

Connector	Rank				Delay	Speed Average	Overall Average
	time to b1	time to b2	time to b3	time to b4			
LCAC	4	1	-	-	4	4.5	3.38
LCU-1600	6	3	-	-	4	6.5	4.88
LCU-1700	6	3	-	-	4	6.5	4.88
SSC	4	1	-	-	4	4.5	3.38
CH-53E	3	-	3	3	1	3	2.6
MV-22	1	-	1	1	3	1	1.4
CH-53K	2	-	2	2	1	2	1.8

Table 12: Overall Connector Rank Average

We can then normalize the overall average listed in Table 12 using the following equation:

$$x' = \frac{x - \min(x)}{\max(x) - \min(x)}$$

Where x is the calculated total average rank from the last column in Table 12 and min(x) is zero and max(x) is seven. The reason zero is used instead of one is the same reason we use seven instead of the actual max(x). Both prevent calculating an x' of 0 or 1, which is considered the fastest possible and slowest possible connector.

Connector	Average Rank(x)	Unity-based Normalization (x')	Feature Scaling (y)
LCAC/SSC	3.38	0.396666667	$13,410
LCU(16/17)	4.88	0.646666667	$21,861
CH-53E	2.6	0.266666667	$9,015
MV-22	1.4	0.066666667	$2,254
CH-53K	1.8	0.133333333	$4,507

[9] Possible bias associated with the rank of time to travel to a node due to dependency of speed, which was also included in the average rank.

$$y = x' * (Max\ Cost - Min\ Cost\ )$$

Table 13: Connector Feature Scaling Values

To determine the feature scaling value (y), multiply the x' value displayed in Table 13 by the difference of the maximum and minimum cost to operate a connector per hour. This cost is a "relative" measure that represents the impact of time as a cost to use in the network flow model. The last column in Table 13 shows that the MV-22 has the lowest "cost" because the value of time has been taken into account whereas the LCU is penalized because of its lack of speed. Next is a side-by-side comparison of this method with the current cost per gallon method.

Side-by-Side Comparison

The difference in cost per gallon to move fuel ashore is shown below for today's MEU in a high threat, minimal weather impact environment. Table 14 shows cost per gallon to a beach node for the original analysis and relative cost per gallon to beach nodes for this Alternative Analysis quick look. Per this table, sea connectors have an increased cost per gallon because a time cost penalty was applied, compared to air connectors whom received a cost discount due to time, thus decreasing the cost per gallon.

	Original Analysis Cost/Gallon					Relative Cost/Gallon			
Connector	B1	B2	B3	B4		B1	B2	B3	B4
LCAC	2.07	2.07	-	-		22.19	22.19	-	-
LCU-1600	1.23	1.23	-	-		20.23	20.23	-	-
CH-53E	10.21	-	10.77	12.17		6.9	-	7.27	8.22
MV-22	15.92	-	16.40	17.60		7.64	-	7.87	8.45

Table 14: Original Analysis Cost vs Relative Cost

Using this method, the optimization was re-run to determine node assignments. The time per sortie was determined using the following equation:

$$time = 2 * \frac{distance\ to\ node}{connector\ speed} + (delay\ time\ for\ load\ and\ unload)$$

Using the calculated time, the node assignment sorties was broken down which determined how long it took to meet fuel demand. Table 15 shows the results from the original scenario and with the relative cost numbers for time.

Comparison of Hours to Deliver Fuel						
Connector	**Destination**	**Number of Sorties**	**Hours per Sortie**	**Total Hours- One Connector per Sortie**	**Total Hours- Two Connectors per Sortie**	**Total Hours- Three Connectors per Sortie**
Original Analysis Results						
LCU-1600	B1	2	4.68	9.36	4.68	-
LCU-1600	B2	2	4.68	9.36	4.68	-
Alternative Analysis Results						
LCAC	B2	1	2.84	2.84	-	-
CH-53E	B1	6	0.93	5.61	2.80	1.87
MV-22B	B1	2	0.98	1.96	0.98	0.65
MV-22B	B4	4	1.18	4.71	2.35	1.57

Table 15: Comparison of Hours to Deliver Fuel

Utilizing this alternate approach, the fuel demand is met faster, and there is a reversal from the original analysis. That is, there is a heavy reliance on air, especially the CH-53E, to bring the most fuel ashore as quickly as possible.

While further sensitivity analysis is required, it would appear that by maximizing the air connectors for fuel delivery, more space and weight is available on the LCU and LCAC to bring other equipment ashore. In this alternative approach, the LCAC only brings 800 gallons ashore of the nearly 3000-gallon capacity it has available.

Conclusions and Recommendations

Conclusions

- Utilizing surface connectors to deliver fuel ashore keeps cost per gallon lower while meeting more of the demand ashore.

- Speed versus cost tradeoff when using connectors.
  - Air connectors deliver fuel faster, but at a higher monetary cost and are more sensitive to threat and environmental impacts. Surface connectors deliver fuel at a lower monetary cost, but at a slower rate.

- Utilize CH-53s to supplement surface connector fuel deliveries to meet demand or reach inland nodes.

- MAGTF planners can use this model during operational planning to identify:
  - Equipment shortfalls
  - Fuel choke points

- Sortie requirements

Recommended Areas for Future Study

- Look at optimizing fuel delivery ashore utilizing a Marine Expeditionary Brigade size force and/or greater.

- Conduct classified study. Utilizing information on actual adversary weapon systems and environmental conditions would provide insight that is more realistic with respect to the sensitivity of connectors to threat and weather.

- Recommended improvements to the model to support future work:
  - Determine the amount of time to deliver the fuel demand ashore.

  - Alter the network flow problem to minimize the amount of time to deliver the demanded fuel ashore. A MAGTF commander operating in an A2/AD environment is not overly concerned with the cost of delivering fuel, but more concerned with the rate at which fuel is delivered and the ability to meet demand.

  - Incorporate land connectors (LSVR, MTVR) into the connector mix to optimize the fuel delivery along the edges as well as the nodes.

  - Incorporate the multitude of configurations that each of the connectors can support. For example, the CH-53 has varying capacities of fuel storage internally and externally that vary in amount and time to deliver.

  - Incorporate the ability to store fuel ashore.

  - Provide an intuitive “feel” and explanations associated with the input blocks so a MAGTF planner, instead of a Systems Analyst, can make inputs.

  - “Harvest” the data output from a scenario run back into Microsoft Excel without having to copy and paste, to include auto populating analysis graphs.

Appendix A

Figure A1 displays the optimized results of the base scenario's range of transportation cost per gallon of fuel delivered ashore. The cost per gallon of fuel results are displayed by each possible combination of threat level, environmental condition, and Marine Expeditionary Unit connector configuration (current or future). The green triangles on figure A1 display the results of the "Air Heavy" base scenarios across the different combinations and show that there is a significant cost increase when relying on more air connectors to deliver fuel than surface connectors.

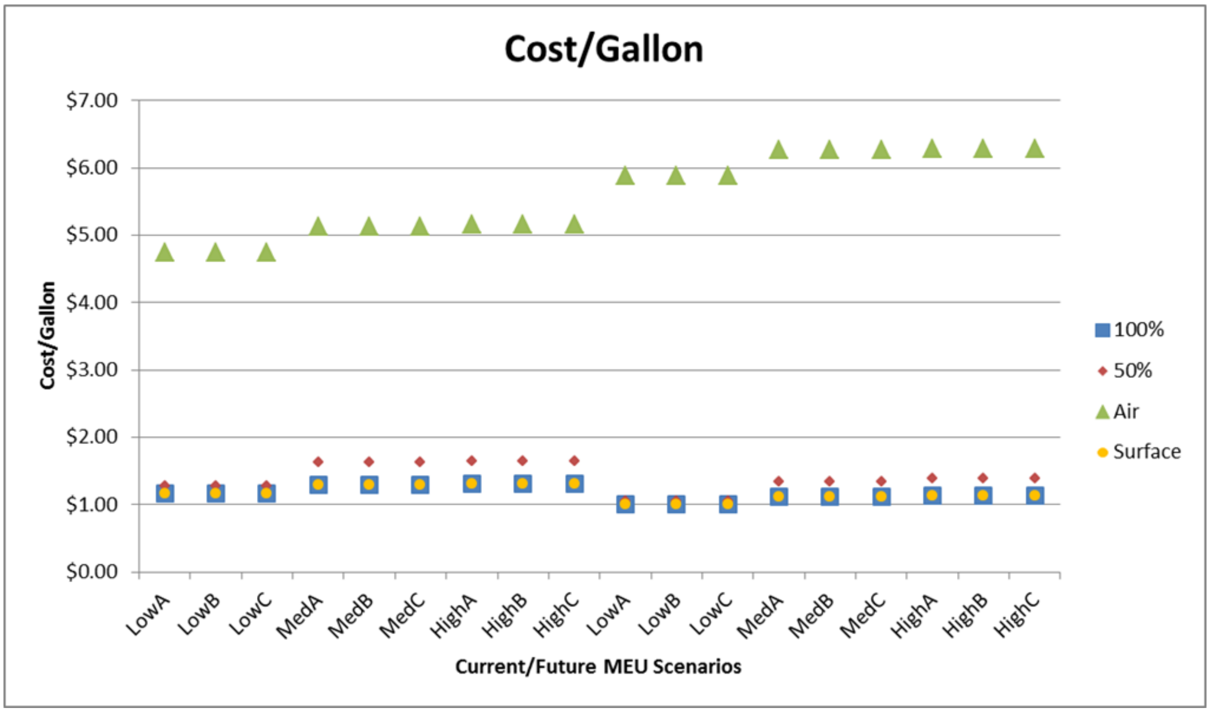

Figure A1: Transportation Cost per Gallon of Fuel Delivered

Figure A2 displays the range of unmet demand for 1000 runs of the model for the four base scenarios, using the current day ARG/MEU, in a low level of threat across the three environmental conditions: A – minimal impact from the environment, B – significant impact to air connectors, and C – significant impact to surface connectors.

The x-axis of Figures A2 through A7 reflects the environmental combinations of the base scenarios of a current or future ARG/MEU across the three threat levels. The left y-axis represents the number of gallons of unmet fuel demand. The green box plots represent the range of the sensitivity results where the top of the green box represents the 75th percentile of the results. In other words, 75% of the results lie at or below the top of the green box. The black line in the middle of the green box represents the median or 50th percentile. The top of the whisker that extends from the top of the green box represents the 90th percentile. The bottom of the green box represents the 25th percentile of the results and the end of a whisker extending from the bottom of the green box represents the 10th percentile of the results. The red diamond on the figure represents the mean average of the results.

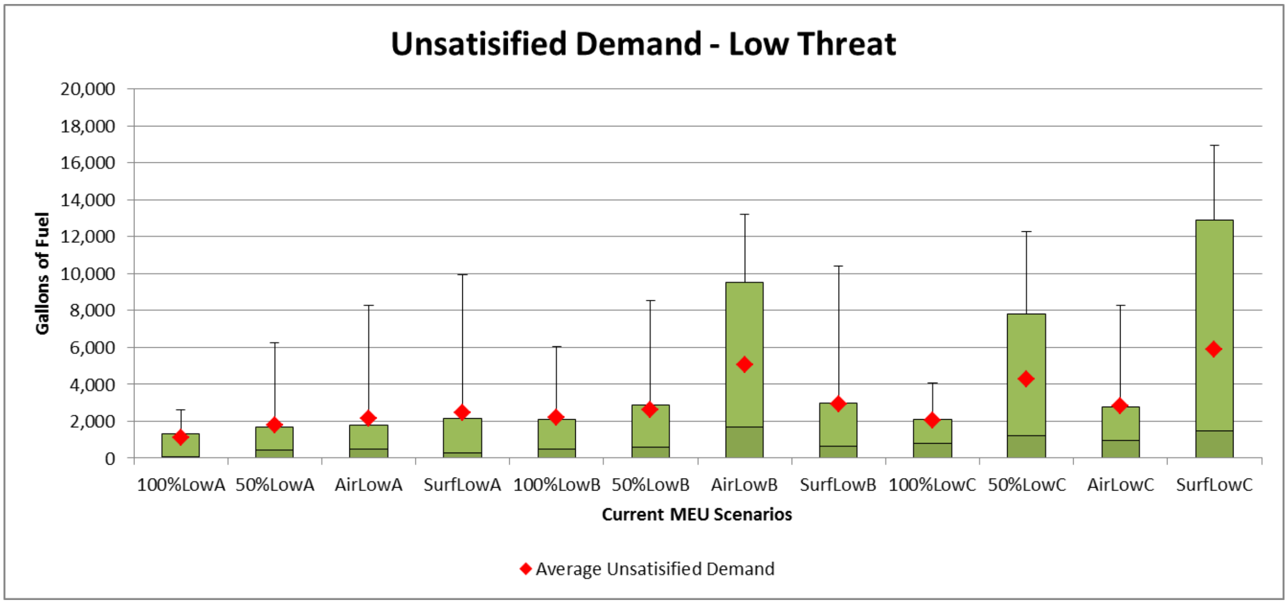

Figure A2: Unsatisfied Demand - Low Threat, Current ARG/MEU

Figure A3 displays the range of unmet demand for 1000 runs of the model using the base scenarios, with the connectors of a future ARG/MEU, in a low level of threat across the three environmental conditions.

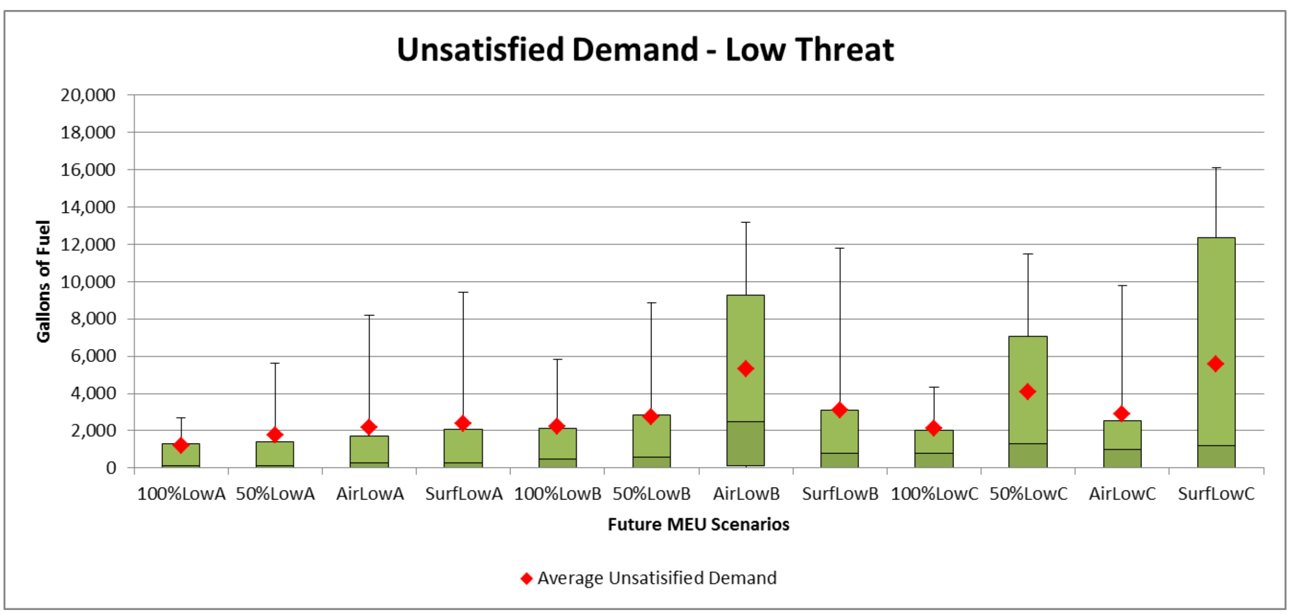

Figure A3: Unsatisfied Demand - Low Threat, Future ARG/MEU

Figure A4 displays the range of unmet demand for 1000 runs of the model for the base scenarios, with the connectors of the current day ARG/MEU, in a medium threat across the three environmental conditions.

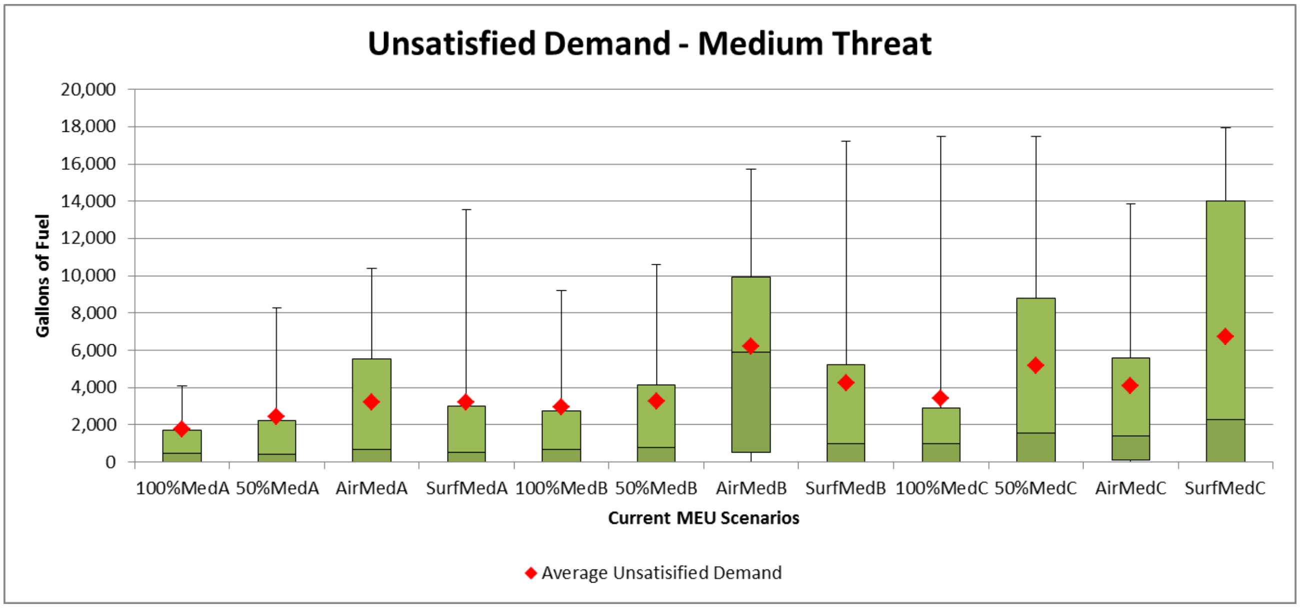

Figure A4: Unsatisfied Demand - Medium Threat, Current ARG/MEU

Figure A5 displays the range of unmet demand for 1000 runs of the model for the base scenarios, with the connectors of a future ARG/MEU, in a medium threat level across the three environmental conditions.

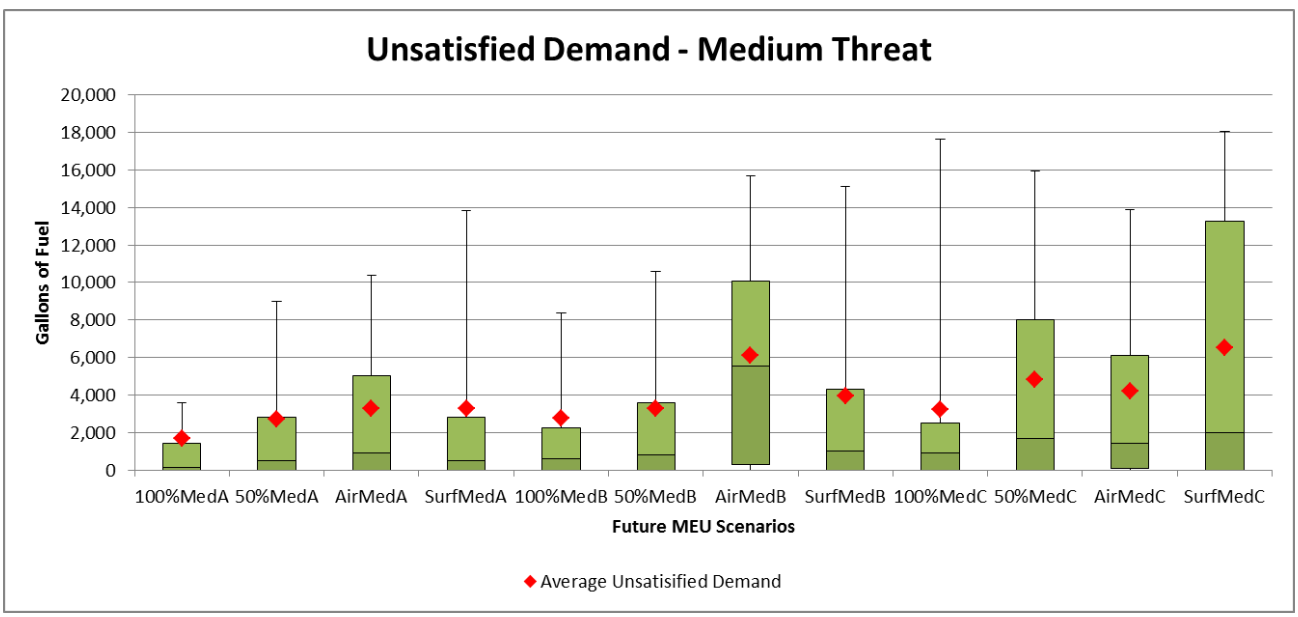

Figure A5: Unsatisfied Demand - Medium Threat, Future ARG/MEU

Figure A6 displays the range of unmet demand for 1000 runs of the model for the base scenarios, with the connectors of a current day ARG/MEU, in a high threat level across the three environmental conditions.

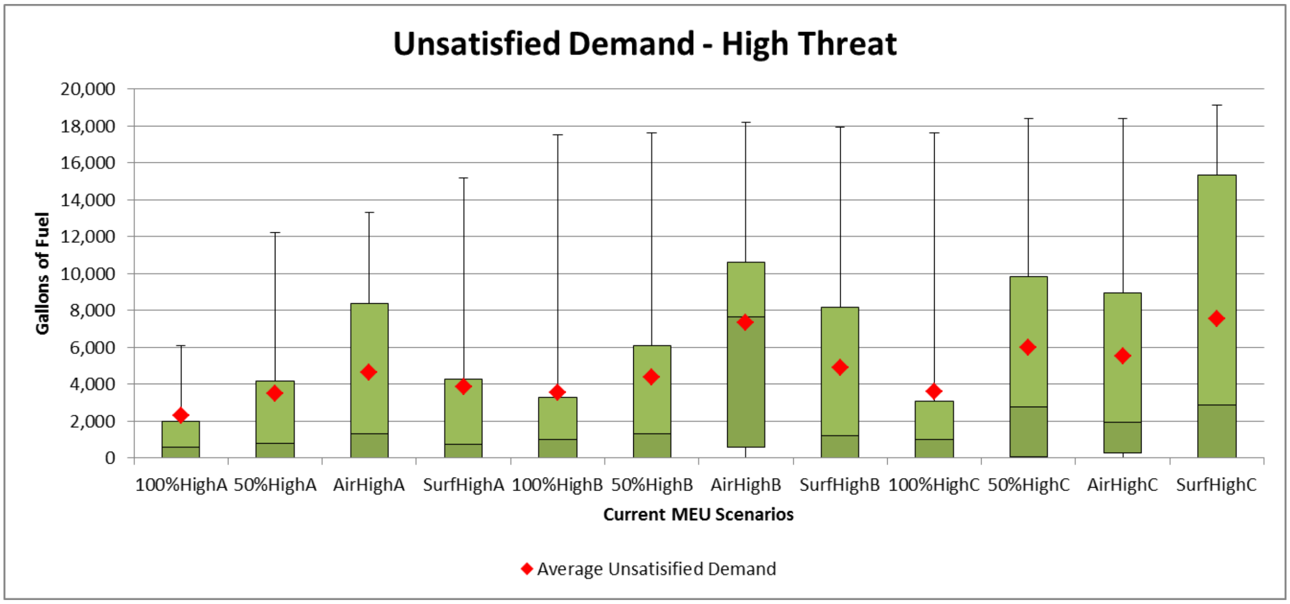

Figure A6: Unsatisfied Demand - High Threat, Current ARG/MEU

Figure A7 displays the range of unmet demand for 1000 runs of the model for the base scenarios, with the connectors of a future ARG/MEU, in a high threat level across the three environmental conditions.

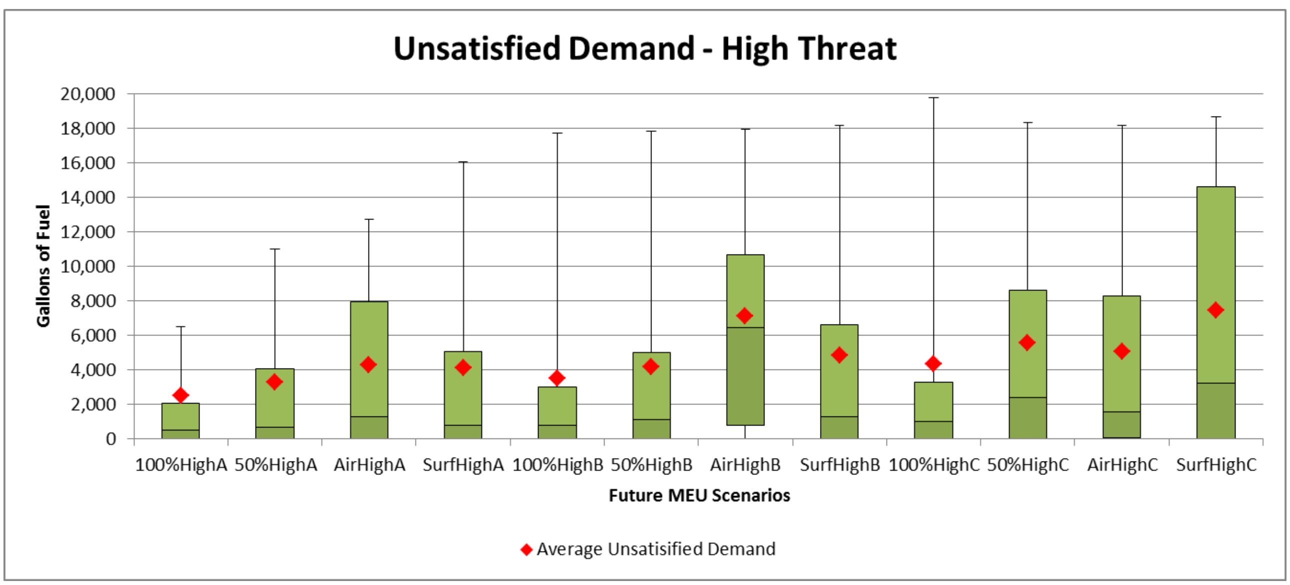

Figure A7: Unsatisfied Demand - High Threat, Future ARG/MEU

THIS PAGE INTENTIONALLY LEFT BLANK

References

24th Marine Expeditionary Unit, USS IWO JIMA ARG, Logistics Pre-Deployment Brief; Information Brief; DC I&L, OPNAV N4, & DCMS.

Aircraft Maintenance Training and Readiness (T&R) Program (AMTRP), 2 October 2009.

Assault Support Tactical Standard Operating Procedures (ASTACSOP), NTTP 3-22.5-ASTACSOP, June 2014.

Deputy Commandant, Aviation Readiness Brief v1.0 given on 26 July 2016.

Dowd, Justin A. Naval Postgraduate School Thesis: Cost Benefit and Capability Analysis of Seabase Connectors, September 2009.

MAGTF Planner's Reference Manual, MAGTF Staff Training Program (MSTP), U.S. Marine Corps, November 2012.

Marine Aviation Plan 2015.

Selected Acquisition Report (SAR): Ship to Shore Connector Amphibious Craft (SSC) As of FY 2016 President's Budget, March 18, 2015.

Selected Acquisition Report (SAR): V-22 Osprey Joint Services Advanced Vertical Lift Aircraft (V-22); As of FY 2015 President's Budget, 16 April 2014.

Selected Acquisition Report (SAR): CH-53K Heavy Lift Replacement Helicopter (CH-53K); As of FY 2016 President's Budget, 18 March 2015.

Total Life Cycle Management Operational Support Tool (TLCM-OST), U.S. Marine Corps Logistics Command, https://lcmi.logcom.usmc.mil/portal/dispatch/show.home

---

[i] Brown, Dell, Formulating Integer Linear Programs: A Rogues' Gallery, Operations Research Department, Naval Postgraduate School Monterey, California 93943 April 2006.Link last accessed on 11 AUG 2016. http://faculty.nps.edu/dell/docs/Brown_Dell_INFORMS_Transactions_on_Education_January2007.pdf